

Nuclear Astrophysics

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Abstract. I review progress that has been made in nuclear astrophysics over the past few years and summarize some of the questions that remain. Topics selected include solar neutrinos, supernovae (the explosion and associated nucleosynthesis), laboratory astrophysics, and neutron star structure.

SOLAR NEUTRINOS AND THE CNO CYCLE

Perhaps no problem in nuclear astrophysics has drawn more attention than solar neutrinos and the associated discoveries of neutrino mass and mixing, the first experimental evidence for physics beyond the minimal standard model. These results grew out of careful solar modeling, patient laboratory measurements of pp-chain nuclear cross sections, and heroic efforts on new experiments. The detectors that have come on line in the past decade and resolved the solar neutrino puzzle, SNO [1] and Super-Kamiokande [2], are remarkable instruments.

But much remains to be done. Direct event-by-event measurements are so far limited to the high-energy ^8B neutrinos, a 0.01% branch in the sun. There are important reasons for extending such measurements to lower energies:

- No phenomenon directly connected with matter-enhanced oscillations, such as spectral distortions or day-night effects due to the earth's matter, has been observed. While indirect evidence of spectral distortions comes from the comparison of GALLEX/GNO/SAGE [3] integrated rates with SNO and Super-Kamiokande results, a direct measurement of changes in $P_{\nu_e}(E_\nu)$ as a function of E_ν is lacking. The parameters deduced from SNO, Super-Kamiokande, and earlier radiochemical experiments predict that low-energy pp and ^7Be neutrinos experience only vacuum oscillations, as the matter contribution to the effective neutrino mass

$$m_{\nu_e}^{2\text{eff}} = 4E_\nu\sqrt{2}G_F\rho_e(x) \quad (1)$$

is insufficient to cause a level crossing for low-energy ν_s . The survival probability for these sources is almost twice that for the high-energy portion of the ^8B ν_e flux. There is some chance that current experiments will be able to see variations in P_{ν_e} . SNO-III (use of ^3He neutron counters) may be able to operate at a lower threshold due to improvements in the charge-current(CC)/neutral current(NC) event separation. KamLAND [4] will be attempting a ^7Be measurement (though this is a difficult task at Kamioka depths), and Borexino [5] may soon turn on at Gran Sasso.

- Measurement of the principal component of the solar flux, pp neutrinos, would isolate one of nature's best calibrated sources of ν_e s. In part because SNO and Super-

Kamiokande measurements of ^8B neutrinos have constrained the temperature of the solar core, the standard solar model (SSM) uncertainty in the pp flux is $\lesssim 1\%$. For this reason pp experiments could improve the accuracy of mixing angle (θ_{12}) determinations. New detectors, such as CLEAN [6] (NC scattering in liquid neon) and LENS [7] (CC scattering in In), are being developed with this goal in mind.

- But perhaps the most intriguing solar neutrinos are those from H-burning through the CNO cycle, which contributes to solar energy generation at about the 1% level. The CNO cycle is the dominant mechanism for stellar energy generation in heavier main-sequence stars, including the very massive popIII stars that formed and produced "first light" (and which turned on the CNO cycle by first synthesizing carbon in the triple-alpha process) [8]. Indeed, nuclear astrophysics arguably began with Bethe's search for the mechanism that could account for energy generation in massive main-sequence stars.

Because the CNO ν flux is proportional to core metallicity Z , a measurement would test this important parameter. It is believed that the sun was highly convective as it entered the main sequence, and thus thoroughly mixed. A plausible consequence – that the zero-age solar core metallicity Z can be equated to today's surface abundance – is a key postulate of the SSM [9]. SSM predictions are sensitive to Z because of the importance of free-bound atomic transitions to the solar opacity. Furthermore, metals can have interesting evolutionary consequences by driving out-of-equilibrium burning of CNO elements in the early sun. Such burning is thought to have powered an early convective solar core for $\sim 10^8$ years.

The sun's metallicity also controls the location of the radiative/convective boundary: a shift to lower Z makes radiative transport in the interior more efficient, and thus leads to a shallower convective zone. Recently improved 3D models of the solar atmosphere have altered the interpretation of photospheric absorption lines, lowering deduced metal abundances by 30% [10]. This has destroyed the previous agreement between SSM predictions and helioseismology: the acoustic modes are quite sensitive to the depth of the convective zone. This is yet another reason for attempting an independent measurement of the sun's interior Z .

UNDERSTANDING CORE-COLLAPSE SUPERNOVAE [?]

Massive stars evolve quickly because their rates of energy generation must be sufficient to sustain hydrostatic equilibrium in deep gravitational potentials. They progress through a series of burning stages and contractions until the final explosive stage of Si burning, where the iron-group ashes that are produced are inert (as these are nature's most tightly bound nuclei). When the iron core grows to the Chandrasekhar mass, it begins a collapse that proceeds on nearly free-fall timescales, as the ability of the electron gas to sustain the star is further eroded by the emission of electron-capture neutrinos and by the excitation of nuclear states, processes taking energy from the gas. Often core collapse leads to ejection of the star's mantle - a supernova (SN) – and a spectacular optical display.

The fundamental problem in understanding the explosion is energy transfer: Because all volume elements in the pre-collapse star are bound gravitationally, the collapse

mechanism must preferentially transfer released energy to the star’s mantle, to account for its ejection. One potential mechanism for energy transfer is the shock wave that forms at the edge of the proto-neutron star, the “sonic point” where the infall velocity matches the local sound velocity. Here pressure waves, initially produced when infalling shells of matter rebound at super-nuclear densities due to nuclear incompressibility, collect after traveling outward from the collapsing star’s dense center. When the sonic point itself comes to rest, the shock wave is released to travel through the star’s outer iron core and mantle. As it does so, it melts the iron into a nucleon and alpha gas. This melting (which requires ~ 8 MeV/nucleon) and neutrino emission from the matter robs the shock of its energy, typically stalling the shock 200 to 300 km from the star’s center. It becomes an accretion shock: the infalling matter crossing the shock front both delivers energy and extracts it, due to nuclear melting, in about equal measures. The shock wave pauses.

Thus other energy transfer mechanisms must operate. The hot, protoneutron star radiates neutrinos, which can scatter off the nucleons in the nucleon gas left in the shock wave’s wake. The relatively strong CC reactions heat the gas, building up pressure that, after a second or so, helps to push the shock wave outward again. However this “delayed mechanism” also fails to succeed in 1D calculations – the regions of the star over which the neutrinos can do useful work and the time over which that work is performed are limited. Matter near the protoneutron star surface, where the neutrino flux is intense, can be heated efficiently. But once $T \sim 2$ MeV is reached, the matter re-radiates neutrinos, effectively halting net heating. Matter further out may not be appreciably heated, given the lower neutrino flux and the short period, ~ 1 s, relevant to the explosion mechanism.

This has led to the recognition that the explosion mechanism may be fundamentally multi-D: 1-D models may place artificial limits on the effectiveness of neutrino heating. In 2- or 3-D, convection can sweep hot, neutrino-heated matter to large radii, cooling it before it can re-radiate neutrinos. This matter is replaced by descending cool material, allowing this matter to be efficiently heated. It is clear that convection allows more energy to be deposited in and retained by the star’s mantle.

The supernova mechanism is a grand-challenge numerical problem, an important but complex process that requires realistic modeling of magneto-hydrodynamics, shock wave propagation, and neutrino diffusion (including transport of energy and lepton number) in multi-D. Important progress has been made. Improvements in the modeling of electron capture and β -decay in the early stages of core collapse have helped refine estimates of the core mass [12]. Simulations in 1-D with full Boltzmann transport and with three-flavor neutrino transport have been performed [13]. Several groups have explored 2- and 3-D models, though necessarily with simplified transport assumptions [14]. New instabilities have been identified, such as a spherical shock instability that influences matter infall and leads to neutron star spin-up [15]. Some of this progress is due to the the Department of Energy’s program for Scientific Discovery through Advanced Computing, which has made core-collapse SN modeling one of its terascale computing applications.

But many challenges remain. Modelers have not yet identified a robust explosion mechanism, perhaps because it is not yet possible to combine multi-D modeling with state-of-the-art microphysics, neutrino transport, neutrino flavor violation, magnetohydrodynamics, general relativity, and rotation. There are significant uncertainties in the input physics, including the nuclear equation of state (EOS) at sub- and super-nuclear

densities, the effects of trapped neutrinos on the MSW potential governing oscillations, and the nuclear physics of finite-temperature reactions. There are also important challenges for experiment, such as detecting all neutrino flavors during the next galactic SN and determining nuclear reaction cross sections important to SN nucleosynthesis – topics for the next two sections of this talk.

NUCLEOSYNTHESIS AND SUPERNOVA NEUTRINOS

A problem likely connected with core-collapse SN is the origin of r-process nuclei. The r- or rapid-neutron-capture-process is thought to produce about half of the nuclei heavier than iron, including all of the transuranics. Candidate astrophysical sites must be explosive, such as core-collapse SN and neutron-star merges, to produce the requisite temperatures and neutron fluences to drive the r-process.

We have learned a great deal about the r-process in the past few years. Abundance data from old metal-poor stars have revealed an r-process distribution for $(Z,A) \gtrsim (56,130)$ that matches solar abundances [16]. As it is believed the surfaces of such stars would have been enriched by very few nearby SN, this suggests that the mechanism that produces high-mass r-process nuclei is a signature event, operating now as it did in early stars. In contrast, the distribution of lighter r-process nuclei varies considerably. The observations, which include chronometer results suggesting different frequencies for events responsible for synthesizing low- and high-mass nuclei, may indicate two or more classes of sites for the r-process, or perhaps a single class where the production of low-mass nuclei is highly irregular [17].

The r-process is a mechanism where nuclei are synthesized under explosive, neutron-rich conditions. Nuclear equilibrium is maintained by $(n,\gamma) \leftrightarrow (\gamma,n)$ reactions, rather than the β -decay equilibrium that defines the valley of stability for ordinary nuclei. The neutron-rich nuclei that exist under such conditions can capture a neutron whenever β -decay occurs, $n \rightarrow p$, as this opens up the needed hole for (n,γ) . Thus the rate of nucleosynthesis is controlled by β -decay. This rate slows near closed shells because repeated β -decays are needed to overcome shell gaps. Thus mass piles up at these points, leading to abundance peaks near $A \sim 130, 195$. After the explosion producing the neutrons ceases, the unstable parent nuclei decay ($n \rightarrow p + e^- + \bar{\nu}_e$) to the valley of stability, thereby producing daughters with N/Z characteristic of stable nuclei.

Of the two sites most often discussed, the expanding, cooling, ν -driven winds of a Type II SN and the decompressing n-rich matter from neutron star mergers, data now favor the former. The two mechanisms involve comparable explosion energies and thus would mix newly synthesized elements into comparable volumes in the interstellar medium. Yet neutron star mergers are roughly 1% as frequent as SNIIs. Thus, to be the dominant site for the r-process, the mass produced per neutron star merger must be 100 times larger. This would be reflected in very large enrichments of isotopes like Eu in early, metal-poor stars – but such enrichments are not seen.

The hot nucleon gas that is left in the wake of the shock, then later blown off the star by the neutrino wind, is thought to be the SN r-process site [18]. This n-rich material, on expanding and cooling, undergoes an α freezeout and then α capture reactions to

produce some heavy seed nuclei of intermediate mass. Excess neutrons are left over. If conditions can be arranged so that the resulting n/heavy seed ratio is ~ 100 , the neutrons will be able to drive an r-process up to the $A \sim 195$ mass peak.

Our lack of understanding of the SNII explosion mechanism leaves open a wide parameter space for the r-process. We do not know what conditions – temperature T , density ρ , and entropy S – describe the trajectories of volume elements ejected from the star. We do not know the neutrino fluence through these volumes: this is crucial because neutrinos are needed to lift the ejected material off the star, yet neutrino reactions can destroy free neutrons and greatly decrease the neutron/seed ratio, thereby making an r-process impossible [19].

New neutrino discoveries have added yet another layer of complexity. The parameter governing flavor conversion in the relevant regions of the star, θ_{13} , has not yet been measured. But unless it is very small, $\lesssim 10^{-4}$, an adiabatic level crossing will occur. The naive position of this crossing is near the base of the carbon zone, at a density of about 10^4 g/cm^3 . But this estimate ignores the contribution of the neutrino background to the MSW potential. It appears, from calculations done to date, that neutrino self-interactions will move the flavor conversion point much deeper into the star [20]. This could have very important consequences, as the conversion might affect both the explosion and nucleosynthesis in important ways. The reason has to do with the higher temperatures characterizing heavy-flavor neutrinos, reflecting their weaker matter couplings. Consequently, a $\nu_e \leftrightarrow \nu_\tau$ oscillation effectively heats the ν_e spectrum, enhancing the CC interactions that govern the n/p ratio and dominate energy transfer from neutrinos to the matter. Flavor conversion could be altered by a variety of effects only poorly understood and modeled, including the density inhomogeneities that are produced by passage of the shock wave and the high-velocity matter flows induced by convection [21]. (The MSW potential also includes a coupling between the neutrino’s velocity vector and weak currents.)

Another topic attracting interest is the possibility of detecting the SN background vs, the “relic” neutrinos that have accumulated during the entire epoch of star formation [22]. Such a measurement should be possible in future megadetectors: Super-Kamiokande has already established a limit that is within about a factor of three of theoretical predictions [23]. Theorists have been busy considering the star formation rate, the stellar mass ranges that might lead to core collapse, and the spectral distortions due to redshift.

SN neutrinos not only govern the conditions for the r-process, but can also directly synthesize new nuclei through the neutrino process. Even far out in the mantle, such as the Ne zone, the neutrino fluence is so high that an appreciable fraction of nuclei, $\gtrsim 0.1\%$ typically, undergo inelastic reactions. Often this leads to excitation of giant resonances followed by the emission of a proton or neutron, and thus the production of a daughter isotope with mass $A-1$. In the past few years some important progress in neutrino process calculations has occurred. Heger et al. extended existing network calculations to heavier nuclei, demonstrating in the process that the rare isotopes La and Ta are likely neutrino process products [24]. La production is dominated by CC reactions off ^{138}Ba , a departure from the usual pattern of NC dominance of neutrino nucleosynthesis. Frohlich et al. [25] and Pruet et al. [26] demonstrated that neutrino reactions on protons could produce a neutron flux sufficient to synthesize p-process nuclei, another example of a CC process.

These CC ν -process channels could be altered by oscillations.

CONCORDANCE IN MICRO-MACRO PHYSICS

One of the remarkable recent achievements in astrophysics is the agreement between the values determined for η , the baryon/photon ratio, from Big-Bang nucleosynthesis (BBN) and from studies of the microwave background and large-scale structure formation [27]. The former involves nuclear microphysics within the first three minutes of the birth of the universe. The latter reflects the large-scale behavior of matter – specifically the baryonic matter-radiation interactions that retard baryon infall into dark-matter halos – at the time of recombination, about 400,000 years after BBN. Thus the agreement ties together two phenomena that occurred at very different times and involved very different scales, one nuclear and one cosmological.

In the future we can look forward to two similar concordance tests. A nonzero η requires an excess of baryons over antibaryons in the early universe. One of the three conditions necessary for baryogenesis is CP violation. But while CP violation has been observed among the quarks, theorists have concluded that the known strength is insufficient to explain η .

However recent discoveries in neutrino physics suggest a resolution of this puzzle. The three-generation neutrino mass matrix has three CP-violating phases, one (Dirac) that could influence long-baseline neutrino oscillation experiments and two (Majorana) that could play a role in low-energy processes like neutrinoless $\beta\beta$ -decay. The quantity that could be tested in neutrino oscillations, e.g., by comparing the probabilities for $\nu_\mu \rightarrow \nu_\tau$ with $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ while accounting for the effects of matter on this difference, involves a product of neutrino mixing parameters, all of which are known to be large except for θ_{13} (not yet measured) and the CP phase. But unless θ_{13} is very small (e.g., $\lesssim 10^{-4}$), there are accelerator strategies that will be able to constrain the CP phase [28].

If significant CP violation occurs among the leptons, it could be communicated to the baryons during the early evolution of the universe, thus accounting for the observed baryon number asymmetry [29]. At least on a qualitative level, a laboratory discovery of leptonic CP violation would put a cosmological observation in accord with what we know about low-energy physics. Making a detailed connection between low-energy observations – either oscillations or the effects of CP phases in $\beta\beta$ -decay mass determinations – and the baryon asymmetry is more difficult. That connection may have to await the invention of a new standard model that explains recent ν discoveries.

There is a second future concordance test that may be more quantitative, the absolute scale of neutrino mass. Because oscillations test only mass differences, laboratory constraints on the neutrino mass scale must come from direct tests in processes like tritium β -decay or indirect tests such as $\beta\beta$ -decay (where masses enter in combination with phases). The current bounds on neutrino mass

$$0.05 \text{ eV} \lesssim \sum_{i=1}^3 m_\nu(i) \lesssim 6.6 \text{ eV} \quad (2)$$

come from the tritium β -decay limit of 2.2 eV, the possibility of a quasi-degenerate neutrino mass spectrum, and the lower bound on mass that can be derived from the atmospheric mass difference δm_{23}^2 . A new tritium experiment now under construction, KATRIN [30], should push the 2.2 eV bound down to about 0.2 eV, while future $\beta\beta$ -decay experiments may probe masses at the level of 10-50 meV [31].

Cosmological analyses – specifically, constraints from cosmic microwave background measurements, large-scale structure surveys, and distance measurements based on Type Ia SN observations – already have lead to the claim [32]

$$\sum_{i=1}^3 m_\nu(i) \lesssim 0.5 \text{ eV}. \quad (3)$$

With anticipated Planck measurements and results from surveys like LSST, this upper bound could drop to 50 meV. Thus there is the possibility that cosmological analyses will discover neutrino mass through its contributions to dark matter. If so, an important “concordance” challenge for laboratory experimentalists will be to verify that mass by direct measurements.

LABORATORY ASTROPHYSICS

Important progress has been made in laboratory nuclear astrophysics. New high-statistics measurements of the reaction ${}^7\text{Be}(p,\gamma)$ important to the pp-chain and solar neutrinos have greatly reduced one of the key uncertainties in SSM ${}^8\text{B}$ neutrino flux predictions [33, 34],

$$S_{17}(0) = 21.4 \pm 0.5(\text{exp}) \pm 0.06(\text{theory}) \text{ eV} - \text{b}. \quad (4)$$

The cross section for ${}^{14}\text{N}(p,\gamma)$, which controls the CNO rate in main sequence stars, was recently remeasured at TUNL [35] and LUNA [36], Gran Sasso’s special-purpose accelerator for nuclear astrophysics. The LUNA results are remarkable and show the potential of underground experiments to reduced backgrounds. The measurements extend to center-of-mass energies of 70 keV, the region of the Gamow peak. Thus not only are the measurements precise, but theoretical uncertainties connected with extrapolating higher energy measurements to the Gamow peak are eliminated. The resulting S-factor,

$$S_{14+1}(0) = 1.61 \pm 0.08 \text{ keV} - \text{b} \quad (5)$$

is almost a factor of two below the former best value. This is a major change, altering for example the evolutionary track that stars follow along the red giant branch, delaying He ignition that marks the transition to the asymptotic giant branch. Consequences include an increase in the estimated ages of the oldest stars in globular clusters of about 0.8 Gyr, a reduction in the flux of CNO solar neutrinos by half, and a delay in the onset of CNO-cycle burning in the early massive stars thought to be responsible for reionization.

The success LUNA is enjoying has increased interest in a nuclear astrophysics accelerator for DUSEL, the NSF’s proposed Deep Underground Science and Engineering

Laboratory. Designs currently under study include both a conventional light-ion machine and a heavy-ion facility for measuring cross sections in inverse kinematics [37]. Such high-intensity machines, coupled with advanced detectors, could improve our knowledge of many critical cross sections.

NEW DATA ON NEUTRON STARS

Neutron stars (NS) are compact objects, with masses in the range of $1.2\text{--}2.0 M_{\odot}$, radii of 7-15 km, and magnetic fields that might range to 10^{15} Gauss. NSs can be seen through their x-ray and optical emissions. The rate at which they cool has been determined from observations. These objects are the focus of a great deal of theoretical attention because their structure depends on properties of strongly interacting matter at high density and unusual isospin – issues include the EOS of such matter, the possibility of phase changes or coexisting mixed phases, etc.

In the past four years there have been several important observations that promise to provide more information on NSs:

- The 1.396 ms (716 Hz) pulsar Terzan5, the fastest yet recorded, was identified [38].
- A double-pulsar system PSRJ0737-3039 with known masses was identified [39].
- A controversial measurement of a large redshift, 0.35, was claimed for H- and He-like Fe lines in x-ray bursts from NS EXO 0748-676 [40].

These results, if confirmed, are important to the goal of understanding the relationship between a NS's mass and radius, an important constraint on the nuclear EOS. It has long been recognized that it is difficult to derive radius constraints from isolated NSs due to uncertainties in distance determinations and atmospheric modeling. Stefan-Boltzmann-like expressions that relate the NS's radius to the observed flux, surface temperature, and distance [41]

$$F_{\infty} = \sigma T_{eff}^4 \left(\frac{R_{\infty}}{d} \right)^2 \quad (6)$$

yield results of questionable accuracy. In contrast, a measurement of the red shift of iron lines coming from the surface of a neutron star would, if confirmed, effectively measure GM/R . As the system in question is an eclipsing binary where a mass determination should be possible, this would determine the radius.

Similarly, milli-second pulsars can place important bounds on NS radii because the NS's equatorial velocity – which would be about $0.25 c$ for Terzan5 – cannot exceed the general relativistic analog of Kepler's velocity. The relationship derived by Lattimer and Prakash [41],

$$v_{\text{Kepler}} \sim 1045 \left(\frac{M}{M_{\odot}} \right)^{1/2} \left(\frac{10 \text{ km}}{R} \right)^{3/2} \text{ Hz} \quad (7)$$

effectively places an upper bound on the radius as a function of M , thereby constraining possible EOSs.

Alternatively, the double-pulsar system PSRJ0737-3039 with known masses should allow observers to determine general relativistic spin-orbit-coupling perturbations gov-

erned by the star’s moment of inertia. The expected accuracy with which the moment of inertia can be determined, given five years of patient observations, is about 10%.

It thus appears that we are about to learn a great deal about NS properties and the nuclear EOS at high density.

There is an important connection between NS properties and the neutrinos produced by the SN parent of the NS. One of the best constraints on M/R might come from integrating the neutrino light curve out to very long times. As 99% of the energy of a SN is emitted in neutrinos – the origin of this energy is the binding of the neutron star – such a measurement would determine the general relativistic analog of GM/R . This requires good knowledge of the distance to the supernova as well as terrestrial detectors capable of measuring the ν_e , $\bar{\nu}_e$, and heavy-flavor neutrino fluxes. As an opportunity to observe a galactic SN may arise only once every 30 years, it is important that “SN watch” efforts include detectors with sensitivities to all flavors and the requisite mass to follow the neutrino light curves out to long times, $\gtrsim 20$ seconds.

There is also a lovely connection with the parity program at Jefferson Laboratory. Competing nuclear EOSs differ in their predictions for neutron-matter pressures P_n and, consequently, NS radii ($\sim P^{1/4}$) because of uncertainties in the treatment of the symmetry energy. The pressure $P_n(\rho_n)$ exerted by neutron-dominated matter is roughly proportional to $dE_{\text{sym}}/d\rho_n$, where ρ_n is the neutron density [42, 43]. The skins of heavy, neutron-rich nuclei are another source of neutron-rich matter. Parity-nonconserving electron scattering can be used to probe these skins, as the weak charge is effectively the neutron number. Typel and Brown [44] have argued that isovector nuclear radius depends on P_n through the relationship

$$\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} \sim P_n (\sim 0.1/f^3). \quad (8)$$

The density at which P_n is probed, of course, is at or below half nuclear density. Thus there remains the problem of extrapolating to densities important to NSs. Nevertheless, an important constraint on the nuclear EOS can be obtained in this way.

CONCLUSIONS AND REMEMBRANCES

I believe at no time has the field of nuclear astrophysics been more exciting than today. The discoveries recently made in neutrino astrophysics have given us our first glimpses of physics beyond the standard model. The neutrino parameters that have emerged from these discoveries are now inspiring a new generation of accelerator neutrino experiments to resolve questions about the neutrino mass hierarchy, θ_{13} , and leptonic CP violation. The results will be important to some of the most interesting open questions in astrophysics: the origin of matter, the contribution of neutrinos to hot dark matter, the mechanism for core-collapse SN.

Laboratory astrophysics will remain important to this field. LUNA’s measurement of the controlling reaction of the CNO cycle underscores how uncertain our knowledge is of key nuclear reactions governing stellar evolution. The field’s most important successes – identification and resolution of the solar neutrino problem, the BBN prediction of η – came from a combination of observation, theory, and laboratory measurements.

Today we need laboratory data not only for cross sections, but also to constrain the new phenomena associated with neutrino masses and mixing. To understand nucleosynthesis in stars, laboratory measurements have to include both stable and unstable targets.

Large-scale computing has become the third leg of nuclear astrophysics, complementing theory and experiments/observations. It now appears likely that the Type II SN mechanism is intrinsically multi-dimensional, and that successful models of the collapse will require the coupling of magneto-hydrodynamics, shock-wave propagation, neutrino transport of energy and lepton number, and rotation. Success in building a “standard model” of SN could produce benefits comparable from those derived from the SSM. The supernova environment tests unique aspects of neutrino physics (θ_{13} , the MSW potential of neutrinos), nucleosynthesis (the explosive conditions necessary for the r-process, the neutrino fluences required for the ν -process), and gravity (gravitational waves tagged by the SN’s optical signal).

Observations of millisecond pulsars like Terzan5 and the double-pulsar system PSRJ0737-3039 suggest that stringent constraints on the properties of dense, neutron-rich nuclear matter will soon be available. NSs could provide crucial constraints on models of the nuclear EOS at high density.

This year is also one for remembering three colleagues who did so much to build this field, Hans Bethe, John Bahcall, and Vijay Pandharipande. Almost every topic in my talk today has roots in the work of these pioneers. Hans is truly the father of nuclear astrophysics, as it was his efforts to understand hydrogen burning as the mechanism for main-sequence stellar evolution that built the bridge from the stars to the laboratory. Because of John’s tireless efforts, the solar neutrino problem was finally recognized as a triumph for quantitative nuclear astrophysics and as the first low-energy manifestation of the physics that lies beyond the standard model. Vijay pioneered techniques to derive the properties of nuclei and nuclear matter directly from NN and NNN forces, including properties of nature’s largest nucleus, the neutron star. We will miss them all.

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